Int J Life Cycle Assess (2010) 15:32–43
DOI 10.1007/s11367-009-0122-4

LCIA OF IMPACTS ON HUMAN HEALTH AND ECOSYSTEMS

Development of regional characterization factors for aquatic eutrophication

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Received: 4 December 2008 / Accepted: 3 October 2009 / Published online: 16 October 2009

Abstract
Background, aim, and scope Life cycle assessment (LCA) has traditionally been considered a site-independent tool, but nowadays, there is a trend towards making LCA more site-dependent. Site-dependent characterization factors have been calculated for regional impact categories such as acidification, terrestrial and aquatic eutrophication, and smog. Specifically, for aquatic eutrophication, characterization factors have been proposed for large geographical areas (mainly European and North American countries). Those factors are not detailed enough for countries which present large geographical, climatic, and economical variability such as Spain. Therefore, this work aims to calculate the characterization factors and the normalization reference for aquatic eutrophication at a regional level, using Galicia (NW Spain), a region with increasing problems of eutrophication, as a case study. Finally, the comparison of the factors obtained here with literature values will be used to analyze the influence of spatial differentiation with increasing coverage of the causality chain.
Materials and methods Particular ecological and economic reasons justify the estimation of characterization factors in Galicia taking into account the specific characteristics of three different ecosystems: Atlantic Ocean, freshwaters, and rias (a specific ecosystem that takes place when a river valley is submerged by a rise in sea level). Taking into account that the state of the art does not allow the calculation of an exhaustive effect factor, the work was focused on the calculation of transport and equivalency factors.
Results Both the principal pathways of transport and the sources of nitrogen (N) and phosphorus (P) were considered to calculate the characterization factors, and from them, the normalization reference was also obtained. An analysis on uncertainty identified the estimations of fractions of NH_x–N and NO_x–N deposited on maritime waters, land, and freshwaters and the fraction of N and P deposited in the soil that reaches water ecosystems, as the more uncertain values.
Discussion As the rias are both N- and P-limited ecosystems, which is a characteristic of coastal and brackish waters in general, the approximation followed in this study to establish characterization factors for the rias can be applied to these types of ecosystems elsewhere (e.g., fiords in Norway) in order to better define aquatic eutrophication impact. By comparing the results obtained with those available in the literature, it is clear that the application of transport factors in the calculation of characterization factors leads to a more realistic definition of aquatic eutrophication, especially when P inputs to the soil are present. When varying the spatial differentiation (continent, country, or region), characterization factors do not vary significantly; however, this variation is likely to increase as long as the definition of the causality chain is improved as it has been reported for other impact categories. In this sense, the equations used in this study can be adapted when

Responsible editor: Jyri Seppälä

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those effect factors became available, being flexible and suitable for future applications in other regions.
Conclusions This study describes the process to calculate aquatic eutrophication characterization factors at a more detailed scale than country, with the particularity of differentiating three different aquatic ecosystems, considering for the first time the rias. The results show the importance of including transport factors in the calculation of characterization factors for aquatic eutrophication, while spatial differentiation is less important at this level of sophistication in terms of coverage of the causality chain.
Recommendations and perspectives The estimation of effect and damage factors is regarded as the next step in the sophistication of this category. On the other hand, the significance of transport factors makes their estimation for other regions than Europe and North America (the only available at the moment) also desirable.

Keywords Aquatic eutrophication · Causality chain · Galicia · Life cycle impact assessment · Normalization · Site-dependent characterization factors · Transport factor

1 Background, aim, and scope

Life cycle assessment (LCA) has traditionally been a site- and time-independent tool, where no consideration is given to when and where emissions take place (Udo de Haes 1996). Characterization factors lack site-dependent information; thus, the resulting impact assessments are site generic (Pennington et al. 2004). For category indicators such as global warming and stratospheric ozone depletion, a site-generic approach is justifiable because the emission location has no influence on either the transport or the effect (Norris 2003). However, increasing research since the late 1990s has demonstrated that the point of emission may have a strong influence on the expected impact for categories including acidification, eutrophication, and smog (e.g., Potting and Block 1995; Potting et al. 1998; Norris 2003; Hauschild et al. 2006). In the concrete case of aquatic eutrophication, one of the reasons why spatial differentiation has rarely been implemented is that fate processes are complex and include transportation between different ecosystems (Finnveden and Potting 1999). However, in the last few years, several sets of country-specific factors have been proposed for this impact category, and new methodologies (RECIPE, TRACI, EDIP2003, LUCAS) have started to include them (Heijungs et al. 2003; Norris 2003; Potting et al. 2005; Toffoletto et al. 2007). Hauschild and Potting (2005) propose a much more reduced scale (the catchments) as the appropriate for eutrophication, although at the present, they consider their approach as impracticable in LCA due to several reasons, such as that the catchments are not identifiable as administrative units or that most of the necessary data are not available for catchments. In the same line, other authors have showed the high difficulty of adapting data from atmospheric models to catchments (Pennington et al. 2005) or areas with similar biogeographic characteristics (Fréchette-Marleau et al. 2008). Therefore, a suitable solution for the moment is the calculation of characterization factors for regions beyond the country scale, especially for countries (such as Spain) with large geographic, climatic, and economic variability (Finnveden and Nilsson 2005).

Galicia (NW Spain) is one of the areas in Europe where a high risk of aquatic eutrophication has been reported (European Environment Agency 2001). It is one of the few European regions that presents high values of N inputs from livestock activities (≥100 kg N/ha) together with medium values of nitrogen fertilizers use (50–100 kg N/ha; European Environment Agency 2000); inputs that have caused, during the last years, an increase in the concentration of nitrate (from <2–3 ppm to 10–20 ppm) in runoff waters in many rural areas in Galicia (Macías et al. 2003). The study of eutrophication at a regional level has also a socioeconomical interest because this impact can affect the production of mussels by aquaculture (270,000 t yr^{-1}) that constitutes one of the major economic sectors in this region (Labarta et al. 2001).

Characterization factors in LCA are defined somewhere along the causality chain of the impact (Potting et al. 2001): either between the emissions and the damage/endpoint (midpoint factors) or at the damage/endpoint (endpoint factors). The tendency in LCA is to define the impact as near to the damage as possible in the causality chain (emission → transport → effect → damage), as long as the characterization factors are kept in similar levels of uncertainty (Hauschild and Potting 2005). Besides, several degrees of the spatial differentiation (whole world, continent, country, region…) can be defined for each level along the causality chain. In order to evaluate the expected improvements associated to those developments (i.e., characterization factors based on different levels of sophistication in terms of the coverage of the causality chain and characterization factors with different degrees of spatial differentiation for a specific level along the chain), a comparison of diverse sets of factors is recommended.

Having in mind all those exposed above, the major objectives of this study are:

- To establish eutrophication characterization factors and normalization reference at a regional scale, using Galicia, as case study
- To observe the influence of spatial differentiation at different levels of sophistication in the modeling of characterisation of aquatic eutrophication

2 Materials and methods

Following the LCIA terminology, the aquatic eutrophication impact caused by a system (A) within a region can be expressed as (adapted from Seppälä et al. (2004)):

$$I_{\mathrm{Eu}}(\mathrm{A}) = \sum_{j=1}^{n} C_{j,i}(\mathrm{A}) \cdot E_j(\mathrm{A}) \qquad (1)$$

where I_{Eu} (A) is the impact value of aquatic eutrophication caused by system A in the area of interest, $C_{j,i}$ (A) is the characterization factor of substance j caused by system A that will reach a given water area i, and E_j (A) is the emitted amount of substance j due to system A.

When considering transport and effect factors (at the moment, the final level of sophistication in terms of the coverage of the chain, damage, is not considered in aquatic eutrophication), characterization factors can be calculated as (adapted from Seppälä et al. (2004)):

$$C_{j,i}(\mathrm{A}) = \eta_{j,i}(\mathrm{A}) \cdot \mu_{j,i}(\mathrm{A}) \cdot Eqv_j \qquad (2)$$

where $\eta_{j,i}$ (A) is the transport factor for substance j and indicates the portion of the emitted substance j that will reach a given water area i ($0 \leq \eta_{j,i} \leq 1$); $\mu_{j,i}$ (A) is the effect factor of substance j and designates the portion of the transported substance j that causes increased production of biomass in a given water area i ($0 \leq \mu_{j,i} \leq 1$), and Eqv_j is the equivalency factor of substance j (usually expressed as kilogram PO_4^{3-} equivalent per kilogram substance j emitted).

Transport factors have only been introduced recently in the calculation of aquatic eutrophication in LCIA on a country scale for European countries or for extended regions of the USA and Canada (Huijbregts and Seppälä 2000; Norris 2003; Toffoletto et al. 2007). In this study, aerial, and soil transport factors for nutrients from major sources are defined at a regional scale.

The actual state of the art regarding aquatic eutrophication does not allow an exhaustive assessment of the effect factor, i.e., whether a nutrient loading actually results in increased biomass growth and what effect this has on the ecological quality of the water (Hauschild and Potting 2005). Thus, the effect factor has not been evaluated in this work ($\mu_{j,i}=1$).

The equivalency factors (Eqv_j) are based on the relative ratio of phosphorus and nitrogen nutrients in the composition of the phytoplankton, the so-called Redfield ratio (C/N/P=106:16:1; Redfield et al. 1963). These factors express all the potential eutrophying impacts produced by different substances using an equivalent unit (normally kilogram PO_4^{3-}). As traditional LCA methodologies (Heijungs et al. 1992) have disregarded the transport and effect factors, characterization factors were equal to the equivalency factors (see Eq. 2).

One important concept when discussing eutrophication is the "limiting nutrient," which means that, in an ecosystem, one nutrient limits the growth of primary producers (and thereby, indirectly affects the whole ecosystem), although there may be an excess of all other nutrients (Finnveden et al. 1992). If an additional amount of the limiting nutrient is added, an increased growth will take place, while an additional amount of the other nutrients will not lead to increased growth. Generally, open seawaters are considered "chronically" limited by N, while lakes and larger slow rivers are limited by P (Blau and Seneviratne 2004). This justifies setting the effect factor for N compounds in freshwater and for P compounds in the ocean equal to 0 because these ecosystems are, generally, P- and N-limited, respectively. As a result, characterization factors are also set to 0 (see Eq. 2).

When studying a particular region, its specific conditions have to be considered. In the case of Galicia, apart from oceans and rivers, another ecosystem has to be considered, as rivers there do not flow directly into the Atlantic Ocean (from now on referred to as the ocean) but through the inner rias (Prego et al. 1999). A ria is a specific ecosystem that occurs when a river valley is submerged by a rise in sea level. These types of marine systems, which have limited exchange with the adjacent ocean, are most susceptible to eutrophication (National Research Council 2000). From the limiting nutrient perspective, coastal and brackish waters like the rias can be limited by either P or N, or both (National Research Council 2000). As exposed above, the rias have also an important economic relevance due to the production of mussels by aquaculture. The ecological differences in the limiting nutrient as well as the economic importance of the rias justify the consideration of the specific characteristics of three different ecosystems (freshwaters, rias, and ocean) for the calculation of characterization factors in Galicia.

When calculating the characterization factors for aerial emissions causing aquatic eutrophication in a region, the relationship between aerial emissions and deposition needs consideration. In theory, emissions from Galicia can travel and affect other ecosystems outside the region, and emissions from other zones can deposit in Galicia and affect its ecosystems. However in this case, the region of interest (which includes the first 200 nautical miles that belong administratively to Galicia) has been considered as a "closed box," where the emissions produced are deposited in this same region, and the influence of the emissions from the neighboring regions has been disregarded. The reasons behind this assumption are:

1) NO_x and NH_x emissions produced in Galicia are mainly deposited in Galicia.

Gallego et al. (2009a, b) established that mobile and industrial sources were responsible for 90% of NO_x

emissions in Galicia. The A9 highway (NW–SW) is the principal route of high capacity in Galicia and the main axis for intraregional and intermetropolitan circulation, with more than 65,000 vehicles per day and almost 65% of the Galician population concentrated around it. Concerning industrial NO_x emissions, the two provinces crossed by the A9 accounted in 2001 for 91.3% of the total of NO_x industrial emissions (Casares et al. 2005). These conditions lead to the high deposition levels observed in the west part of the region (Fig. 1a). The high deposition located in the NE of the region (a sparsely populated area with little industrial presence) is surprising. The presence of high mountains, which can cause lower mobility of air and cause NO_x to stagnate, and the proximity of the highway A6 can be considered as reasonable explanations for this high deposition. In any case, there is no evidence that the majority of the NO_x deposited is from outside Galicia.

A large proportion of the NH_x emitted locally is deposited in the immediate neighborhood of the source rather than being transported in large distances (Sutton et al. 1994; Dragosits et al. 2002; Spangenberg and Kölling 2004; Spokes and Jickells 2005). This low mobility is also confirmed in Galicia: Gallego et al. (2009a, b) identified dairy cows and broilers as the main sources of NH_x in the region (38.8% and 41.1% of the total, respectively), and their production is concentrated in the north east and south part of the region, correspondingly (Medio Rural 2003), which are the locations where more NH_x is deposited (see Fig. 1b). The high depositions detected in the NE of Galicia are also in agreement with the hypothesis of lower mobility of air due to the presence of high mountains exposed for NO_x.

2) Inputs of NO_x and NH_x from neighboring regions to Galicia can be disregarded.

This statement is based in the analysis of the levels of deposition and emission from NO_x and NH_x in Galicia and in the neighboring regions (<200 km of distance from the Galician frontier) reported by the Cooperative Program for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP 2008). It should be noted that the EMEP grids do not correspond with the limits of the Spanish regions, and therefore, the emissions and deposition have been proportionally distributed in the case of "frontier" grids. Additionally, the values calculated by EMEP are based on modeling of the data reported by only 16 monitoring stations in Spain and five in Portugal, and therefore, this data must be analyzed with caution when applied at such local scale. With these limitations in mind, Table 1 shows that the level of emissions and deposition in Galicia and neighboring regions are quite similar (the differences are under 10%), which can be interpreted in two ways:

- The net flux of emissions (input–output flows) is close to 0; that is, Galicia exports NO_x and NH_x to its surroundings in a similar amount that it imports emissions from neighboring regions. Having this in mind, a variation of the emissions in Galicia (and therefore, a variation on the depositions elsewhere) will

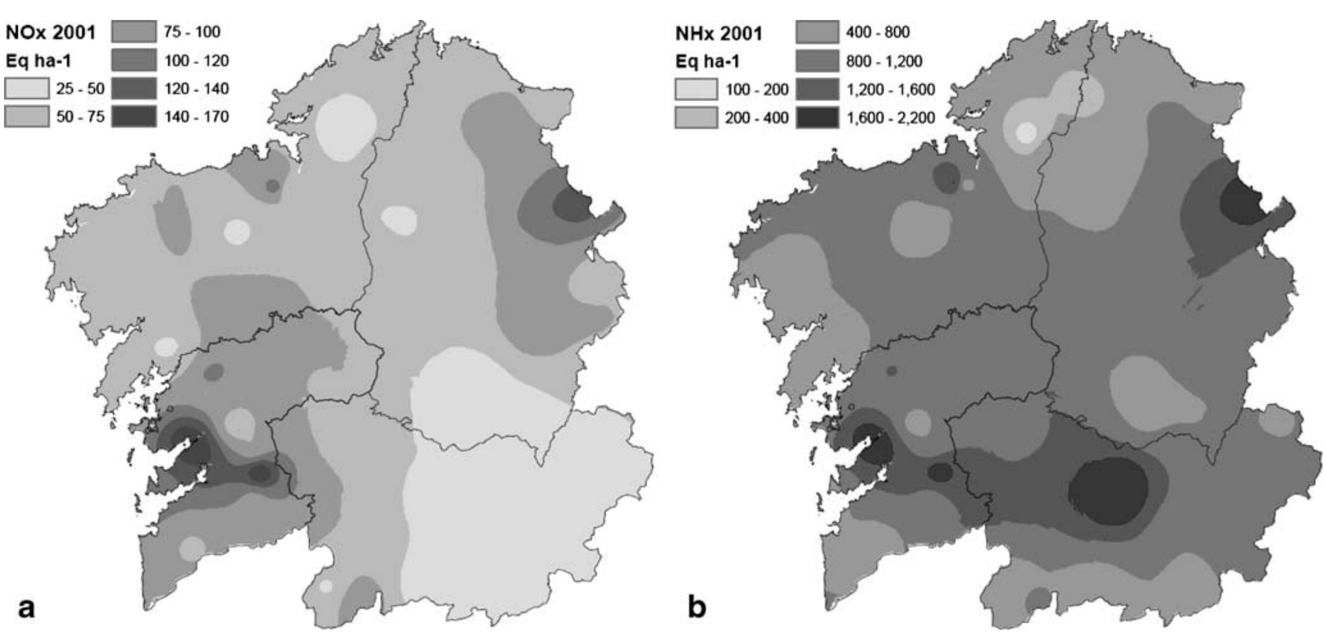

Fig. 1 Deposition levels of NO_x (**a**) and NH_x (**b**) in Galicia (adapted from Macías et al. (2003))

Table 1 Emission and deposition levels in Galicia and in the neighboring regions (from reported data by EMEP 2008)

	Emissions			Depositions		
	Galicia	Neighboring regions[a]	Difference[b] (%)	Galicia	Neighboring regions[a]	Difference[b] (%)
NO_x (t/km^2)	2.49	2.70	8.43	2.06	2.23	8.25
NH_x (t/km^2)	0.49	0.48	–2.04	0.41	0.40	–2.44

[a] Two hundred kilometers from the Galician border

[b] Difference in comparison with Galician values

produce a similar impact on the aquatic eutrophication of those regions as the neighboring regions present very similar biogeographical characteristics (type of vegetation and its distribution, land use, climate, rivers…) to Galicia (Bunce et al. 2002). As a result, even when produced in other regions, the impact caused by Galician emissions is well described by the characterization factors calculated here.

- The pattern of dispersion is similar both in the neighboring regions and in Galicia (the emissions are deposited near to where they were produced), and thus, the external flux of NO_x and NH_x to Galicia can be ignored.

3 Results

The principal pathways considered in this study for the transport of N and P compounds within freshwaters, rias, and ocean are described in Fig. 2. The main sources of these nutrient pollutants are: atmospheric deposition, inputs applied directly to the soil (mainly agricultural), and municipal/industrial wastewater (Hauschild and Potting 2005).

3.1 Atmospheric deposition

The eutrophying pollutants in air are NO_x (generally calculated as NO_2) and NH_x (as NH_3) (Huijbregts and Seppälä 2000; Huijbregts and Seppälä 2001; Seppälä et al. 2004; Potting et al. 2005). Air emissions of P have been neglected, as they have no relevance in the eutrophication of surface waters (Potting et al. 2005). As an example, in the case of the Netherlands, the atmospheric emission is less than 3% of the waterborne emission while only a minor part of that atmospheric P will, through topsoil erosion, reach surface water (Berdowski and Jonker 1994).

NO_x–N or NH_x–N emitted in Galicia can settle directly into maritime waters (concept that includes rias + ocean; pathway A in Fig. 2a) or can reach these waters indirectly (first into freshwater environments or the land and then into marine waters, pathways B–F, C–E–F). Equation 3 follows from Eq. 2 to estimate the characterization factors for the air emissions of NO_x–N and NH_x–N, considering their effects in marine waters (note that for freshwaters, characterization factors for NO_x–N and NH_x–N are 0 as they are P-limited ecosystems):

$$C_{j,\mathrm{air},i} = \left[\omega_{j,i} + \varepsilon \cdot \left(\varphi_{j,\mathrm{freshwater}} + \psi_{j,\mathrm{land}} \cdot \tau_j \cdot \sigma_{j,i}\right)\right] \cdot \mu_{j,i} \cdot Eqv_j \tag{3}$$

where $C_{j,\mathrm{air},i}$ is the characterization factor for an air eutrophying pollutant j (NO_x–N or NH_x–N) that produces its effect in water area i (marine waters). The fraction of aerial pollutant j that directly reaches the water area i, the freshwater ecosystems, and the land are represented by $\omega_{j,i}$, $\varphi_{j,\mathrm{freshwater}}$ and $\psi_{j,\mathrm{land}}$, respectively. Elimination caused by denitrification in anaerobic zones in freshwaters has been

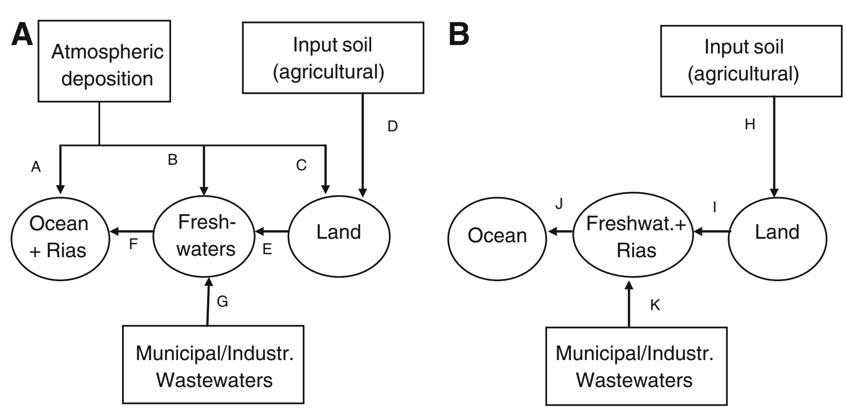

Fig. 2 Principal pathways considered for N (**a**) and P (**b**) transport in Galicia

stated as 30% (Heijungs et al. 2003; Potting et al. 2005; Toffoletto et al. 2007), so only 70% of the nitrogen present in freshwaters will be transported to the marine waters (ε=0.7). The fraction of substance j present in the soil after plant uptake is expressed with τ_j. The fraction of substance j present in the soil after plant uptake and that reaches freshwater systems is expressed with $\sigma_{j,i}$.

The proportion of N that reaches the soil and then is transported to water ecosystems is difficult to assess, and therefore, values were taken from the literature. The factors developed by Hauschild and Potting (2005) for the proportion of nitrogen deposited in arable and natural land available after plant uptake and based on the texture of the soils have been used for the calculation of $\tau_{NOx\text{–}N}$ and $\tau_{NHx\text{–}N}$. In Galicia, soil textures vary from sandy (soils developed on granitic rocks) to loamy (developed on schist and slates; Rodríguez and Macías 2006), but detailed information on the percentage of each type of soil texture is not available. Therefore, considering the factors developed by (Hauschild and Potting 2005), a range between the values for loamy ($\tau_{NOx\text{–}N}=\tau_{NHx\text{–}N}$=0.18) and sandy soils ($\tau_{NOx\text{–}N}=\tau_{NHx\text{–}N}$=0.25) can be considered, which represents the best value corresponding to the lowest possible fraction of nitrogen available in the soil after plant uptake and the worst one that is the highest possible, respectively. Assuming the precautionary principle of worst case, the value of $\tau_{NOx\text{–}N}=\tau_{NHx\text{–}N}$=0.25 was considered for the calculation of characterization factors.

Specific values for $\sigma_{NOx\text{–}N,i}$ and $\sigma_{NHx\text{–}N,i}$ for Galicia are neither available for Galicia, and again, literature values were necessary. Using the model CARMEN (CAuse effect Relation Model to support Environmental Negotiations), Hauschild and Potting (2005) established approximate factors that represent the proportion of N and P available in the soil that reaches inland and maritime waters for different countries (including Spain) directly and indirectly (flowing first through ground waters). The authors recommended the use of the inland water factor as the best estimation for Spain: $\sigma_{NOx\text{–}N,j}=\sigma_{NHx\text{–}N,i}$=0.87 (Hauschild and Potting 2005).

Finally, in order to estimate the factors $\omega_{j,i}$, $\varphi_{j,\mathrm{freshwater}}$, and $\psi_{j,\mathrm{land}}$ (Table 2), the deposition levels of NO_x–N and NH_x–N were calculated for the year 2001 using rainfall composition data recorded at 23 monitoring sites from the governmental monitoring network of atmospheric pollutants in Galicia and from the monitoring networks of the power stations of As Pontes and Meirama (Rodríguez and Macías 2006). Galicia has been considered as a “closed box” (see Section 2), and therefore, the emissions produced in Galicia are completely deposited in this same region, and the influence of the emissions from the neighboring regions has been disregarded. With these assumptions, the measured values of NH_x–N and NO_x–N deposition for the year 2001 in freshwater (3,129 t NO_x–N and 4,571 t NH_x–N) and terrestrial ecosystems (21,401 t NO_x–N and 35,457 t NH_x–N) have been divided by the total emissions of these pollutants (38,731 t NO_x–N and 57,731 t NH_x–N) previously estimated by Gallego et al. (2009a, b). No data to directly evaluate the deposition levels of nitrogen compounds on marine ecosystems are available, so we assume that the emissions produced in Galicia that do not deposit to land or freshwater (14,201 t NO_x–N and 17,703 t NH_x–N) will deposit directly to the sea.

The fractions deposited to marine ecosystems obtained in this study (0.37 for NO_x–N and 0.31 for NH_x–N) are slightly higher than those from the literature (Huijbregts and Seppälä 2000; Huijbregts and Seppälä 2001) for Spain (0.23 for NO_x–N and 0.19 for NH_x–N) and West Europe (0.31 for NO_x–N and 0.27 for NH_x–N). In order to analyze the influence that the fraction of NO_x–N and NH_x–N deposited on sea water has on the characterization factors, a sensitivity analysis was performed using values of $\omega_{j,i}$ for Spain and West Europe found in the literature, changing $\varphi_{j,\mathrm{freshwater}}$ and $\psi_{j,\mathrm{land}}$ proportionally and keeping the other parameters constant. The results (Table 3) show that the variations between the different characterization factors obtained are small (between 0.17–0.21 kg PO_4^{3-} eq/kg NO_x–N and 0.15–0.19 kg PO_4^{3-}eq/kg NH_x–N), and considering the region under study, the values for Galicia were selected.

3.2 Municipal and industrial wastewaters

Another major source of nutrients to aquatic systems is direct emission of (treated or untreated) household and

Table 2 Fractions of NO_x–N and NH_x–N emitted in Galicia that directly reach freshwaters ($\varphi_{j,\mathrm{freshwater}}$), land ($\psi_{j,,\mathrm{land}}$), and maritime waters ($\omega_{j,i}$)

Substance (j)	A. Total emission (t)	B. Deposition freshwaters[a] (t)	C. Deposition land[b] (t)	D. Deposition maritime waters D=−(B+C)	G. $\varphi_{j,\mathrm{freshwater}}$[a] G=B/A	F. $\psi_{j,\mathrm{land}}$[b] F=C/A	E. $\omega_{j,i}$ E=D/A
NO_x–N	38,731	3,129	21,401	14,201	0.08	0.55	0.37
NH_x–N	57,731	4,571	35,457	17,703	0.08	0.61	0.31

[a] Also includes urban areas and infrastructures that have been considered as waterproof, and thus, the waters will reach the aquatic ecosystems through the sewage systems

[b] Includes agricultural areas, forests, and grassland

Table 3 Characterization factors for aerial NO_x–N and NH_x–N with different values of $\omega_{j,i}$, $\varphi_{j,\text{ freshwater}}$, and $\psi_{j,\text{land}}$ for Galicia, Spain, and West Europe

Area (*i*)	Region	Substance (*j*)	$\omega_{j,i}$	ε	$\varphi_{j,\text{freshwater}}$	$\psi_{j,\text{land}}$	τ_j	$\sigma_{j,i}$	$\mu_{j,i}$	$Eq\upsilon_j$[a]	$C_{j,\text{air},i}$[a] (Eq.3)
Maritime waters	Galicia	NO_x–N	0.37	0.7	0.08	0.55	0.25	0.87	1	0.42	0.21
		NH_x–N	0.31	0.7	0.08	0.61	0.25	0.87	1	0.42	0.19
	Spain	NO_x–N	0.23	0.7	0.10	0.67	0.25	0.87	1	0.42	0.17
		NH_x–N	0.19	0.7	0.09	0.72	0.25	0.87	1	0.42	0.15
	West Europe	NO_x–N	0.31	0.7	0.09	0.60	0.25	0.87	1	0.42	0.20
		NH_x–N	0.27	0.7	0.09	0.70	0.25	0.87	1	0.42	0.18

[a] Expressed as kilogram PO_4^{3-} equivalent per kilogram substance *j* emitted

industrial wastewater through the sewage system. Considering the pathways from Fig. 2 A–B (G–F, K–J), Eq. 4 develops Eq. 2 to estimate the characterization factors for the emissions of N and P contained in wastewater:

$$C_{j,\text{water},i} = \left(\varepsilon \cdot \gamma_j\right) \cdot \mu_{j,i} \cdot Eq\upsilon_j \qquad (4)$$

where $C_{j,\text{water},i}$ is the characterization factor for the eutrophying pollutant *j* (N or P) present in household or industrial wastewaters that reaches water area *i* (freshwaters, rias, or ocean) after wastewater treatment. The removal by denitrification in anaerobic zones of freshwater is again represented by ε, and the fraction of *j* that remains in the water after wastewater treatment is represented by γ_j.

Taking into account an equivalent population (including official and stational population as well as industrial sources) of 5,190,475 in Galicia (de Medio Ambiente 2001) and an individual production of 9.2 g N per day (Klepper et al. 1995) and 1.6 g P per day (Metzner 2001), Galicia produces 17,430 t N per year and 3,031 t P per year. However, only 32% of the population is connected to secondary wastewater treatment and an additional 2.5% to primary (Consellería de Medio Ambiente 2001). These treatments achieve removals of 62% and 10% for N and 42% and 10% for P, respectively (Folke 1996; Potting et al. 2005; Gallego et al. 2008). Thus, 3,459 t N and 409 t P (20% and 13% of the total amount emitted, respectively) will be depurated, and therefore, γ_N=0.80 and γ_P=0.87.

Table 4 summarizes all estimated values of the parameters needed, following Eq. 4, in order to calculate the characterization factors for N and P in wastewater considering its effects in rias, ocean, and freshwater.

3.3 Inputs applied to the soil

Nutrients can be applied directly to the soil and then transported to water ecosystems producing aquatic eutrophication. The use of chemical fertilizer and the application of manure in agriculture are the most significant sources of these nutrients. Following the recommendation of Potting et al. (2005), the same characterization factors have been established for manure and chemical fertilizers because when calculated individually, the results are very similar. From Eq. 2, and considering the pathways from Fig. 2 A–B (D-E-F, D-E, H-I-J, H-I), Eq. 5 expresses the characterization factors for N and P inputs applied to the soil.

$$C_{j,\text{soil},i} = \left(\varepsilon \cdot \tau_j \cdot \sigma_{j,i}\right) \cdot \mu_{j,i} \cdot Eq\upsilon_j \qquad (5)$$

where $C_{j,\text{soil},i}$ is the characterization factor for the substance *j* (N or P) introduced in the soil by different inputs (normally fertilizers or manure) to the water system *i* (freshwater, rias, or ocean). As described above, ε represents the denitrification that takes place in anaerobic zones, τ_j describes the fraction of substance *j* after plant uptake, and $\sigma_{j,i}$ the fraction here of that reaches freshwater systems.

Table 4 Characterization factors for N and P contained in wastewaters

Substance (*j*)	Water area (*i*)	γ_i	ε	$\mu_{j,i}$	$Eq\upsilon_j$[a]	$C_{j,\text{wastewater},i}$[a] (Eq.4)
N	Maritime waters[b]	0.80	0.7	1	0.42	0.24
	Freshwaters	0.80	0.7	0[c]	0.42	0.00
P	Ocean	0.87	1	0[c]	3.06	0.00
	Freshwaters + rias	0.87	1	1	3.06	2.66

[a] Expressed as kilogram PO_4^{3-} equivalent per kilogram substance *j* emitted

[b] Maritime waters = ocean + rias

[c] The ocean is considered N limited and the freshwaters P limited

Table 5 Values of characterization factors for N and P applied directly to the soil

Substance (*j*)	Water area (*i*)	ε	τ_j	$\sigma_{j,i}$	$\mu_{j,i}$	$Eqvj$[a]	$C_{j,\mathrm{soil},i}$[a] (Eq.5)
N	Maritime waters[b]	0.7	0.25	0.87	1	0.42	0.06
	Freshwaters	0.7	0.25	087	0[c]	0.42	0
P	Ocean	1	0.10	0.03	0[c]	3.06	0
	Freshwaters + rias	1	0.10	0.03	1	3.06	0.01

[a] Expressed as kilogram PO_4^{3-} equivalent per kilogram substance *j* emitted

[b] Maritime waters = ocean + rias

[c] The ocean is considered N limited and the freshwaters P limited

In order to establish the fraction of N and P present in the soil after plant uptake (τ_N and τ_P), the factors developed by Hauschild and Potting (2005) were used in a similar way as in Section 3.1. In the case of N, a range of 18–25% of the nitrogen applied will be available after plant uptake (thus, τ_N=0.18–0.25), being the highest value the one applied here. In the case of P, Hauschild and Potting (2005) established a general value of 10% (τ_P=0.10) regardless the soil texture.

Values of $\sigma_{N,i}$ and $\sigma_{P,i}$ for Galicia are taken from the values reported by Hauschild and Potting (2005) for Spain (see Section 3.1): $\sigma_{N,i}$=0.87, $\sigma_{P,i}$=0.03.

Table 5 summarizes the values of all parameters estimated in order to calculate the characterization factors for N and P in inputs applied to the soil (mainly fertilizers and manure), considering effects in ria, ocean, and freshwaters, as well as the characterization factors obtained.

3.4 Normalization reference

The calculation of all these characterization factors (see Tables 3, 4, and 5) also allows us to estimate the normalization reference. Total emissions for a reference year in a reference region are generally used to calculate normalization reference in LCA (Huijbregts and Seppälä 2001), and consequently, the emissions in Galicia in 2001 were chosen here as the reference scenario (Table 6).

3.5 Uncertainties

An analysis of the uncertainties shared by all eutrophication methodologies (such as considering the Redfield ratio as constant or ignoring the specific sensitivity of the receiving environments; Seppälä et al. 2004) is beyond the scope of this study. Thus, this section only deals with the specific uncertainties associated with the input data required specifically for this methodology.

The characterization factors here obtained depend on several input variables with inherent uncertainties. Among them, the main sources of uncertainty in the calculation of these factors are:

- The estimation of the fractions of N and P deposited to the soil that reaches water ecosystems. The values used to estimate the available fractions of nitrogen and phosphorus deposited to the terrestrial ecosystems and remaining there after plant uptake are estimates, and due to the absence of specific data, the worst case has been assumed. In order to calculate the quantity of N and P present in the soil that reaches water ecosystems, only data from Spain as a whole were available.
- The calculation of the fractions of aerial NO_x–N and NH_x–N deposited to marine waters, freshwaters, and land is also an important source of uncertainty,

Table 6 Characterization factors and normalization reference in Galicia in 2001

Substance (*j*)	A. Emissions (t) in 2001[a]	B. Characterization factor ($t\ PO_4^{3-}$ eq/t substance *j* emitted)	C. Normalization per substance ($t\ PO_4^{3-}$ eq/year) C=B	D. Normalization reference ($t\ PO_4^{3-}$ eq/year) D=ΣC
NO_x–N (air)	38,731	0.21	8,134	37,549
NH_x–N (air)	57,735	0.19	10,970	
N (water)	17,430	0.24	4,183	
P (water)	3,031	2.66	8,062	
N (soil)	99,303[b,c]	0.06	5,958	
P (soil)	24,248[b]	0.01	242	

[a] de Medio Ambiente (2004), Gallego et al. (2009a, b), Asociación Española de Fertilizantes (2008)

[b] Only agricultural inputs (manure and fertilizers) have been considered

[c] Net emissions of N (after volatilization of N aerial compounds)

especially when assuming Galicia to be a "closed box" for NO_x–N. The justification of this hypothesis, already described above, must be empirically proved. In order to apply this methodology to other regions, each case must be analyzed individually to determine which amount of the emissions are deposited in that same region and which ones are deposited in other regions.

- Finally, the removal of N and P through wastewater treatment plants can vary locally (e.g., based on type of technology, characteristic of the incoming water, and management of the facilities), and this effect has been disregarded by using average values of N and P efficiencies for both primary and secondary treatments.
- Other minor sources of uncertainty come from neglecting P emissions to air and from assuming that, on average, 30% of N in freshwater is converted into N_2 due to denitrification.

4 Discussion

Hauschild et al. (2008) have started to analyze all life cycle impact assessment methods available at the moment in order to recommend the best methodology for each impact category to the European Commission. In the specific case of aquatic eutrophication, Hauschild et al. (2008) consider that the impact assessment methodology has to discriminate the exposed ecosystems according to (among other facts) the limiting nutrient (N for oceans and P for freshwaters). In this study, a further step is proposed by considering a third type of ecosystem (rias) and, therefore, increasing the level of discrimination. In the case of rias, the differentiation from the point of view of limiting nutrient (they can be limited by either P or N and even can change along the year) is common to all brackish and coastal ecosystems and, therefore, can be applied easily to these types of ecosystems elsewhere (e.g., fiords in Norway).

The results obtained in this study are compared with other values available in the literature (see Table 6) in order to analyze the effects of spatial differentiation at different levels of sophistication in terms of the coverage of the causality chain. Characterization factors calculated by Heijungs et al. (1992) are equivalency factors that disregard fate because they have neither spatial differentiation (they can be used equally in any part of the world) nor transport considerations (all the nutrients emitted are assumed to reach the water systems producing eutrophication). Those from Huijbregts and Seppälä (2001) do include transport factors but with a low level of spatial differentiation (considering Europe as a whole). The last set of values corresponds to 32 European countries, which represent a higher spatial differentiation, and were reported by Potting et al. (2005).

Characterization factors for aquatic emissions of N and P are excluded from the comparison because the inclusion of transport factor has no sense (substances are already in the water). In LCA, the agricultural topsoil is normally considered as a part of the product system (Weidema and Meusen 2000) so the inventory data (on which the characterization factor will be applied) stand for the fraction of available nutrients after plant uptake (τ_j); however, the characterization factors for N and P applied to the soil calculated for Galicia include this element (see Table 6), and therefore, they need to be recalculated (Table 7) without taking into account the values of τ_j estimated, or a double-counting would occur.

As shown in Table 7, the differences are much larger due to different levels of sophistication in terms of coverage of the causality chain (inclusion or not of transport factors) than due to spatial differentiation where the maximum difference between all characterization factors for Europe, Spain, and Galicia is for aerial NO_x–N which is four times greater in Galicia that in Spain. In the same line, the differences between the characterization factors for 32 countries proposed by (Potting et al. 2005) were also small

Table 7 Comparison of the characterization factors without fate for, Europe, 32 countries in Europe and Galicia

Substance (j)	Characterization factors (kg PO_4^{3-}/kg substance j emitted)			
	Equivalency factors without fate[a]	Europe[b]	32 countries in Europe[c]	Galicia
NO_x–N (air)	0.42	0.16	0.02–0.09 (0.05)	0.21
NH_x–N (air)	0.42	0.14	0.02–0.18 (0.09)	0.19
N (soil)	0.42	0.10	0.11–0.27 (0.26)	0.26[d]
P (soil)	3.06	0.09	0.06–0.46 (0.09)	0.09[d]

[a] Heijungs et al. (1992)

[b] Huijbregts and Seppälä (2001)

[c] Lower and higher values reported; values for Spain in brackets (Potting et al. 2005)

[d] Modified values without taking into account the nutrients consumed by the plants (τ_j)

(a maximum of a factor of 9 for aerial NO_x–N and a factor of 8 for phosphorus applied to the soil). However, this does not imply that spatial differentiation has no sense, as significant differences have been reported (Huijbregts et al. 2000; Krewitt et al. 2001; Potting et al. 2005; Posch et al. 2008) for other impact categories (such as terrestrial eutrophication or acidification) that have already advanced in the coverage of the causality chain, i.e., the effect factor has been included. For example, Potting et al. (2005) included the effect factor when calculating characterization factors for 44 European regions (most coinciding with countries) and reported differences bigger than a factor of 1,000 for acidification and a factor of 500 for terrestrial eutrophication.

Bearing all this in mind, the calculation procedure for characterization factors described here is ready for a future development of effect factors for aquatic eutrophication, being also flexible and suitable for its application in a future spatial differentiation in other regions.

5 Conclusions

This study demonstrates the possibility of calculating aquatic eutrophication characterization factors for aquatic eutrophication and normalization reference at a regional scale. The specific characteristics of three different ecosystems (freshwaters, rias, and ocean) have been considered in the calculation of characterization factors for aquatic eutrophication. The main focuses of uncertainty of Galician characterization factors are, due to lack of specific data, the estimation of the fractions of N and P deposited to the soil that reaches water ecosystems and the calculation of the fractions of aerial NO_x–N and NH_x–N deposited to marine waters, freshwaters, and land.

By comparing the results obtained with those available in the literature, it is clear that the application of transport factors in the calculation of characterization factors leads to a more realistic definition of aquatic eutrophication, especially when P inputs to the soil are present. Considering what has happened with other impact categories, the importance of spatial differentiation between regions will increase as the inclusion of more levels of the causality chain advances.

6 Recommendations and perspectives

At present, calculation of effects and damage factors in LCA is not viable for aquatic eutrophication. Their estimation is the next step in the sophistication of this category and should be the focus of future scientific study. In this sense, the Directive 2000/60/EC (also known as "EU Water Framework Directive") can be of help as every member states must set up "target nutrient loads" for their rivers. Besides, it is expected that when coming into force, this directive will lead to a more accurate basis for transport and effect factors of nutrients in inland and coastal waters in different parts of the European Union (Seppälä et al. 2004). All these data will, at the same time, allow a better spatial differentiation and reduce the uncertainties associated to calculation.

On the other hand and taking into account the relevance of the transport effect, it would be interesting to see their development for regions outside Europe and North America, the only places where they have been calculated so far.

Acknowledgments This work has been funded jointly by the Galician Government (project reference—PGIDIT04TAL269003PR) and the Spanish Ministry of Education and Science (project reference—NOVEDAR-Consolider CSD 2007-00055). We are grateful to both organizations for their financial support. The authors would like to thank Dr. José Potting for her helpful comments and recommendations.

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